

# **RXTE observations of GRS 1915+105**

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## ABSTRACT

The galactic superluminal motion source GRS 1915+105 was observed with the RXTE satellite at several occasions during its ongoing active state. The observed X-ray intensity changes drastically on a variety of time scales ranging from sub-seconds to days. In particular, the source exhibits quasi-periodic brightness sputters with varying duration and repetition time scale. These episodes occur occasionally, while the more common X-ray intensity variations are faster with much smaller amplitudes. The spectrum during the brightness sputters is remarkably different from the spectrum of the mean high state emission. We argue that such sputtering episodes are possibly caused by a major accretion disk instability. Based on the coincidence in time of two radio flares following the observed X-ray sputtering episodes we speculate that superluminal ejections (as observed from GRS 1915+105 during earlier activity periods) are related to episodes of large amplitude X-ray variations.

*Subject headings:* X-rays: stars — stars: individual (GRS 1915+105) — accretion disks — instabilities

## 1. Introduction

On 1992 August 15 the WATCH detectors on *Granat* discovered a new X-ray transient (Castro-Tirado *et al.* 1992) which was designated GRS 1915+105. Follow-up monitoring with WATCH and BATSE (Harmon *et al.* 1992) revealed an unusual light curve consisting of a 3 month rise, an 8 month high-intensity plateau phase, and a 2 month decline. A variable radio source was found with the VLA (Mirabel *et al.* 1993a) inside the  $\pm 10''$  X-ray error circle (Greiner 1993), as well as a variable infrared source (Mirabel *et al.* 1993b, Castro-Tirado *et al.* 1993). The soft X-ray spectrum as seen with the ROSAT PSPC on several occasions is strongly absorbed ( $N_{\text{H}} \approx 5 \times 10^{22} \text{ cm}^{-2}$ ; Greiner 1993) supporting the earlier conjecture that GRS 1915+105 is located behind the Sagittarius arm, i.e. at a distance greater than 8 kpc (Greiner *et al.* 1994). Indeed, later HI measurements suggest a distance of about 12.5 kpc (Mirabel & Rodriguez 1994). The optical counterpart (at the radio position) was only detected in the I band at 23.4 mag, while it is fainter than 25.9, 26.1 and 26.1 mag in B, V, and R, respectively (Boër, Greiner & Motch 1996).

An outburst with a light curve similar to the one described above (but with shorter duration) occurred between December 1993 and April 1994, at which time GRS 1915+105 was observed in a remarkably high radio state. Further radio monitoring revealed radio structures travelling at apparently superluminal speed (Mirabel & Rodriguez 1994) making GRS 1915+105 the first superluminal source in the Galaxy. Until then, apparent superluminal motion was only observed in AGN, the central engines of which are generally believed to be massive black holes. This similarity suggests that GRS 1915+105 harbors a stellar-sized black hole. Indirect support for this hypothesis was provided by the discovery of the second galactic superluminal motion source GRO J1655–40 (Zhang *et al.* 1994), for which a mass function larger than  $3 M_{\odot}$  was subsequently established by optical radial velocity measurements (Bailyn *et al.* 1995).

## 2. ASM discovery of renewed activity in GRS 1915+105

The RXTE All Sky Monitor (ASM) observes bright X-ray sources in the range of  $\sim 2$  to 12 keV using position-sensitive proportional counters placed below coded masks. X-ray intensity measurements are derived from the deconvolution of overlapping mask shadows from each X-ray source in a camera’s field of view. There are 3 cameras (SSCs) in the ASM, and the field of view of each camera is  $6 \times 90$  degrees FWHM. Histograms of detected counts vs. anode wire position are telemetered for each SSC in 3 separate energy bands (1.3–3.0 keV, 3.0–4.8 keV, and 4.8–12.2 keV). Detector problems were experienced soon after launch, but performance was stabilized with an operating duty cycle  $\sim 40\%$  (limited to low-background regions of the XTE orbit). This data rate provides  $\sim 7$  celestial scans per day, with sky coverage obtained in a series of 90 s stationary exposures (“dwells”) followed by an instrument rotation of 6 degrees. Data collection has been ongoing with at least 1 SSC since 1996 February 21.

The data analysis utilizes all 8 anode wires in SSC1 and 6 anode wires in each of SSC2 and SSC3. The fine details of the instrument calibration are still being refined, and the present analysis is subject to a systematic error of about 3% for uncrowded source regions (such as around GRS 1915+105), as inferred from the rms deviations observed in the Crab Nebula. Further details of the instrument and the data analysis methods are provided by Levine *et al.* (1996). For the ASM observations of GRS 1915+105 reported below, we select results from individual SSC dwells and normalize all of the results to the throughput of SSC1, in which the Crab yields a total counts rate of 73 SSC c/s. For the present investigation, we exclude measurements in which the angle between the X-ray source and the Earth is less than  $75^\circ$ . We also exclude observations in which a camera’s field of view contains more than 15 potential X-ray sources or observations in which any 2 sources are within a rectangle of  $0.1 \times 6.0$  aligned perpendicular to the anode wires.

The ASM light curve for the period 1996 February 21 to June 21 is shown in Fig. 1. Extreme and evolving levels of X-ray variability were confirmed by the appearance of rapid variations (s to min) seen in the ASM time series data (collected in parallel with position histogram data) during many dwells when GRS 1915+105 was in an SSC field of view. An ASM alert led to RXTE pointed observations with the PCA and HEXTE instruments. The times of the pointed observations are marked with an asterisk in the top panel of Fig. 1.

### 3. Pointed RXTE Observations

The Proportional Counter Array (PCA) on RXTE (Zhang *et al.* 1993) consists of 5 nearly identical xenon-filled proportional counter units (PCUs) each with 1250 cm<sup>2</sup> of collecting area. The detectors are sensitive to X-rays between 2 and 60 keV with 17% energy resolution at 6 keV. The Crab produces 2500 cts/s/PCU (2–60 keV) while the background count rate is typically  $\sim 20$  cts/s/PCU. On April 6, 9, 17 and May 14, only 3 PCUs were used due to an operational problem. On April 15 the gain of all 5 PCUs was lowered by 30%. Due to the steep energy spectrum (see below) we discuss the PCA but not the HEXTE data in this short communication.

#### 3.1. Temporal characteristics

The X-ray light curves reveal a variety of features, one of which is large amplitude intensity variations. This is very similar to the behavior seen from dwell to dwell in the ASM, as well as in the light curves of individual dwells.

We identify the following properties in the light curves of GRS 1915+105 (see Figs. 2, 3 and 4):

- Repeating pattern of brightness sputters: In 5 of the pointed PCA observations, Apr. 6, May 21 and 26 and Jun 16 and 19 we find large, eclipse-like dips in the X-ray flux, which we call sputters. During these sputters the flux drops from  $\approx 2\text{--}3$  Crab to a momentary lull at about 100–500 mCrab and then shoots up again. The spectrum softens dramatically during the brightness sputters. The sputters occur quasiperiodically with a recurrence time of about 250 sec during the first observation (see top part of Fig. 3). The decline to the low level (lull) typically takes 3–5 sec and the rise to the high level 5–10 sec. The lull duration varies irregularly, with a mean value of between 30–50 sec during the first observation and only a few seconds in later observations. The low-intensity value during the lull is surprisingly constant with time during the first observations. It is also interesting to note that the rms variability during the brightness sputters is much smaller than elsewhere. During the June 16 and 19 observations the brightness sputters all have a small flare lasting 10s at the start of the sputter.
- Large-amplitude oscillations: On Apr. 6 the X-ray intensity starts oscillating with increasing amplitude towards the lull, with the last oscillation before the lull nearly reaching the low-intensity level of the lull (top of Fig. 3). On May 26 we see extremely large amplitude oscillations with an amplitude of nearly 3 Crab and periods of 30–100s.
- Flare following lull: On one occasion on Apr. 6 the intensity remained low for over 300 sec and there is a large (to  $>3$  Crab) flare following this lull, that is spectrally invariable, in sharp contrast to the spectral softening seen during the brightness sputters. After the flare there is a long delay before sputtering resumes (Fig. 3).
- Brief flares in prolonged lulls: During a major lull observed on May 26 (see Fig. 4) the source exhibited a flare lasting 5s. Before this flare the intensity went below the

QPO floor. About 400 seconds later another sharp flare occurs as the source intensity climbs back up. This complex pattern is repeated almost identically 4925 seconds later (Fig. 4). Unfortunately, the observation ended before we could see if the pattern repeated more than twice.

- Fast oscillations: Between the episodes of large-amplitude variations the variations are more regular, developing into clearly visible quasi-periodic oscillations (20 mHz- 67 Hz) which have rich phenomenology including spectral characteristics and dynamically changing amplitudes and frequencies. These features will be discussed in a following paper (Morgan *et al.* 1996).

The ASM light curve of GRS 1915+105 is marked by an interval of extreme and random variations that were in progress on Feb. 21 and continued until April 7 (MJD 50180; see Fig. 1). A later period that can be characterized as a series of X-ray flares (hours to days) occurred from May 17 to July 16 (MJD 50220-20280), and this interval was followed by 25 days of apparently steady emission at 0.51 Crab. The PCA observations with highest amplitudes of both X-ray flux and variability occurred on April 6, May 20–26, and June 11–19, and these sample both the intervals of random variability and X-ray flaring seen with the ASM. A more detailed analysis of the temporal evolution of the quasi-periodic oscillations and their energy dependence are presented in a forthcoming paper (Morgan *et al.* 1996).

### 3.2. Spectral characteristics

While a complete spectral analysis is beyond the scope of this letter, a few general features can be deduced already at this early stage. The spectra during the April 9 through 29 observations are complex and rapidly variable. Most of these spectra are rather steep

and fall off beyond 20 keV.

The hardness ratio panels in Figs. 3 and 4 already demonstrate that the spectrum of the X-ray emission during the lulls is softer than during the high-intensity states, i.e. these lulls are not caused by absorption or any low-energy cut-off. We have selected photons (for individual layers and single PCA units using the `ftools` command `saextract`) at different time intervals corresponding to these two intensity states. Slew data at the end of the observation was used for background subtraction and the spectral fitting was done using the XSPEC package (Shafer *et al.* 1991). The gross energy distribution of the high-intensity emission (on April 6) can be described by a power law model with photon index  $\alpha = -1.6$  and an high-energy cutoff around 5 keV while the high-intensity spectra on May 20 and 26 require a second component above  $\approx 15$  keV. The spectrum during the lulls (April 6, May 26) is well represented by a two component model, e.g. a disk blackbody plus a power law with photon index  $\alpha = -2.2$  without a high-energy cutoff. The spectrum during the rebound is an extremely steep pure power law ( $\alpha \approx -4.5$ ). As can be inferred from the hardness ratio plot, there are no major spectral changes during the decay phase between lulls before the onset of the large-amplitude oscillations. But during these oscillations the spectrum gets harder and softer than the mean on the same time scale as the oscillations.

#### 4. Discussion

The previously known properties of GRS 1915+105 had signified an unusual nature, compared to the known types of high-energy transients: The relativistic radio jets, slow rise time, the spectral characteristics, as well as the lack of a systematic flux decay are markedly different from black hole transients like e.g. GRS 1124–68 or GRO J0422+32. With our data from RXTE observations of GRS 1915+105 these differences are even more pronounced.



The absence of pulsed emission (Morgan *et al.* 1996) suggests that the observed X-ray emission does not come directly from the surface of a rotating, magnetic compact object. On the other hand, the strong variability during the high-intensity states on time scales well below one second indicates that the emission region cannot be a large and hot corona. We therefore tentatively assign this emission to an accretion disk.

GRS 1915+105 as observed in April 1996 with RXTE is at least a factor of 3 more intense than it was when observed by ROSAT (Greiner *et al.* 1994) and ASCA (Nagase *et al.* 1994, Ebisawa & White 1995) during previous active states. At a distance of GRS 1915+105 of 12.5 kpc (Mirabel & Rodriguez 1994), the mean, unabsorbed luminosity in the 1–25 keV range is of the order of  $10^{39}$  erg/s during the high-intensity states (a factor three more than has been noted previously, e.g. Sazonov & Sunyaev 1996). This is well above the Eddington luminosity for a neutron star with any reasonable mass, suggesting that the system contains a black hole.

As evidenced by the energy spectra (softening), the brightness sputters are not absorption dips. Occultation events are unlikely due to two reasons: First, the occulting body would have to be large in comparison to the projected X-ray emitting area (in order to explain the short rise and fall times) which is difficult to reconcile if the emitting area is an accretion disk, even if only a fraction of the disk dominates the emission. Second, unless such an occulter were related to the large-amplitude oscillations in the X-ray flux, there is no reason to have the intensity drops always occur during times following large amplitude oscillations. It is therefore more plausible to relate the large-amplitude oscillations as well as the sputters to a single phenomenon, e.g. an accretion disk instability. This is supported by the fact that the large-amplitude oscillations show similar spectral changes as the sputters.

If one relates the strongly variable X-ray emission to the inner part of an accretion disk, and since the spectrum during the lulls is markedly different, consequently one has

to suppose that the inner part of the accretion disk is changed drastically. The accretion flow in the inner regions of an accretion disk around a compact object has been proposed to undergo a sonic transition before falling supersonically onto the compact object (Matsumoto *et al.* 1985). As the inner accretion disk is re-filled rather quickly, it is certainly always far from being in a steady state. In fact, the observed X-ray spectrum in the 2–20 keV range is completely dissimilar to a steady, multicolor disk blackbody except during the lulls.

It is worth noting that the rebound after lulls does not correspond to the release of energy which is “missing” over the lull duration. This is a suggestive hint that the energy is channeled into a different energy form, possibly kinetic. Episodes of large amplitude variations (= major instabilities in our interpretation) have been observed on April 6, May 20 and 26 as well as June 16 and 19, 1996 (Fig. 2). Interestingly, these times coincide with radio flares (with a delay between 1–5 days) reported for the period of May 23 through 26 (Pooley 1996), and another one during June 17 through 22 (Pooley, *priv. comm.*). Therefore, the episodes of large amplitude X-ray variations may be related to the formation of jets. We also note that during these episodes the X-ray spectrum shows a distinct hard component (though varying) which seems to be missing at other times. This component might enable the detection of GRS 1915+105 by BATSE (see Zhang *et al.* 1996 for the May 20 through 26 period). Previous radio monitoring of GRS 1915+105 and GRO J1655–40 has resulted in the perplexing result that not all X-ray active states were accompanied by radio emission (e.g. the April 1995 and the August 1995 activity period of GRO J1655–40, Foster *et al.* 1996), suggesting that radio emission (jets) are not related simply to X-ray high states. If the correlation of radio emission following episodes of large amplitude, erratic X-ray variations will be found on further occasions, the clue might have been found to relate jet formation to X-ray behavior.

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Fig. 1.— Light curve of GRS 1915+105 as measured with the RXTE/ASM in the 2–12 keV range (top panel) and spectral hardness ratio, defined as  $HR2 = \text{flux (5–12 keV)} / \text{flux (3–5 keV)}$  in the lower panel.

Fig. 2.— Light curves of GRS 1915+105 as measured with the RXTE/PCA (2–60 keV range, but dominated by photons below 25 keV due to the spectral shape). Shown is the count rate per PCUs (note the different scales) at 1 sec time resolution, with each panel showing one orbit of selected pointed observations. All the variations in X-ray count rate are due to GRS 1915+105, i.e. Earth occultations and SAA passages are removed, while dead time is negligible and has not been corrected for (which is 1% per 1000 cts/s/PCU).

Fig. 3.— Blow up of a part of the light curve of GRS 1915+105 on April 6, 1996 showing the quasi-periodically repeating pattern of 30 sec duration brightness sputters (top) and the major lull (bottom). The top panel of each plot shows the count rate per PCU while the lower panel shows the hardness ratio (count ratio in the (4.4–25 keV versus 2–4.4 keV band) at the same time resolution of 1 s (time along the abscissa refers to the time labeled in the top panel). Note the overshooting after the rebound and the long waiting time until sputtering resumes. Even during the lull, the background rate (about 5 cts/s) is still negligible as compared to the source rate.

Fig. 4.— Blow up of a part of the light curve of GRS 1915+105 on May 26, 1996. The top panel of each plot shows the 2–25 keV count rate in one PCU while the lower panel shows the hardness ratio (count ratio in the 4.4–25 keV versus 2–4.4 keV band) at the same time resolution of 1 s.









